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Productive and Economic Assessment of Agroecosystems in Chimborazo, Ecuador: Integrating Geographic Information Systems and Biodiversity Management for Sustainable Rural Development

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The Andean region of Ecuador, due to multiple anthropogenic pressures, requires sustainable systems that are resilient to the effects of climate change. As a possible alternative to reach a consensus on achieving greater productivity and economic viability within a framework of respect for natural resources. An exploratory study was conducted to evaluate the productive and economic performance of a dairy system in the province of Chimborazo, adding the integration of geographic information systems (GIS) and biodiversity indicators. To obtain the information, on-site visits were made using structured surveys and interviews to obtain real information on costs and production dynamics. Meanwhile, using GIS tools, land use was characterised, as well as ecological indicators of species richness, Shannon diversity index and soil quality. A marked seasonality in milk production was observed ($P < 0.001$), which was most noticeable in April and May (716-728 L/month), decreasing significantly in December to January (578-590 L/month). Annual production reached 156,282 L, with an average of 8.9 L/cow/day, reaching a production cost of USD 0.43 per litre and an approximate annual income of USD 78,141 from milk sales. Furthermore, it has been shown that the implementation of silvopastoral systems and riparian protection zones results in greater biodiversity (20 species; Shannon index of 2.88 and > 0.90 in soil quality) when compared to a traditional monoculture system. In conclusion, the use of ecological, spatial and economic indicators confirms that the implementation of sustainable practices diversifies land use, significantly improving the resilience of the livestock system and is therefore a valuable tool for decision-making towards achieving sustainable systems for the high Andean ecosystem.
Keywords: Sustainability; Livestock small producers; Andean region, dairy cows.

INTRODUCTION

Chimborazo, located in the central highlands region of Ecuador, is characterised by small and medium-scale livestock production, which accounts for approximately 82% of the total, thus ensuring that local demand is met. In fact, milk production is an important source of income for families (Caballero-Serrano et al., 2017; Fuentes et al., 2023; Lozano et al., 2020). Despite this behaviour, specifically in livestock farming in the province of Chimborazo, there are countless biotic and abiotic factors that reduce the productive efficiency of livestock in one way or another. For this reason, dairy farms should transform into more competitive systems with a responsible approach to sustainability. In this regard, it is essential to evaluate economic performance and management practices in order to identify which processes in the production system could be optimised, thereby improving profitability.

According to Duchi Yaguachi et al. (2023), Echeverría-Puertas et al. (2023), and FAO (2009), the components that have a marked influence on the sustainability of livestock farming are animal health, labour, and infrastructure. Furthermore, according to several authors, rational management of biodiversity ensures the proper sustainability of fragile ecosystems (Painii-Montero et al., 2020). Therefore, the diversification of clean technologies such as silvopastoral

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systems, combined with ecological transition zones or ecological reserve buffers, are fundamental to resource conservation and land use (Vivar-Arrieta et al., 2023) and resilience to climate variability (Sánchez and Mendoza, 2019). Despite several studies having been conducted, the quantification of variables that claim to extrapolate the results broadly to producers is limited (Córdova et al., 2018), As clear evidence of the benefits for systems in ecologically vulnerable conditions (Bilsborrow et al., 2004; Vargas-Tierras et al., 2018; Viteri-Salazar and Toledo, 2020).

On the other hand, in a world where cutting-edge technology makes use of countless technological tools for better resource management, the adoption of several of these (technological resources) is an optional strategy for better management and decision-making in agricultural and livestock activities. In this sense, Geographic Information Systems (GIS) constitute a powerful analytical platform for carrying out land use planning or rational management of biotic resources. This allows for the generation of information and analysis of data on biodiversity indicators and practices related to how different actions are being developed in livestock systems (Gabriele et al., 2023; Reddy et al., 2016; Mohammed Hamud et al., 2019). Another advantage of using GIS compared to traditional methods is its ability to detect different patterns of spatial variability in productive or ecological issues. This facilitates accurate and optimal decision-making regarding land use and distribution. However, despite all this scientific progress, in developing countries, there are few or no studies that integrate GIS tools to monitor economic and biodiversity indicators in livestock systems in high Andean conditions in Ecuador.

In another context, in developed or higher-income countries, these types of multi-criteria analysis technologies are already being implemented to carry out comprehensive assessments and attempt to identify sustainability variables in agricultural production systems. This has yielded interesting results in terms of food self-sufficiency, significantly reducing dependence on the acquisition of external inputs with a high carbon footprint, as is typical in traditional systems. However, following the same pattern observed in other latitudes, the application of biodiversity metrics and economic variables at the dairy farm level has been limited. Another point to consider is that, from an economic point of view, seasonality in production, combined with the variability of milk prices, has a significant economic impact on livestock farming. This has a marked effect on the complexity of financial planning, generating cash flow imbalances when production dynamics are not properly taken into account. For this reason, multidisciplinary teams should be formed to develop analytical frameworks that take these conditioning factors into account, contributing to management and administration in terms of economic, social and productive sustainability. Within this context, this study analyses the productive and economic performance of a typical dairy farm in Chimborazo, Ecuador. The research therefore includes a cost-benefit analysis and a spatial assessment based on the use of GIS to determine indicators of how biodiversity is managed.

MATERIALS AND METHODS

***Area study*:** This research was conducted in the province of Chimborazo, Ecuador, located at coordinates 78°28′ south latitude and 78°28′ west longitudes, at an altitude of approximately 2,750 metres above sea level. The study area has a temperate Andean ecosystem with average temperatures ranging between 12 and 14 °C. Likewise, the annual rainfall is in the range of 900-1100 mm/year. The property where the livestock system is located has a herd of 500 head of cattle, of which 120 were lactating during the study.

***Experimental procedure*:** For this research project, on-site visits were made to the livestock farm with the aim of analysing the production operating system and formulating guidelines to optimise production costs. For this reason, information was obtained through structured surveys and interviews to record inventories. This information was crucial for identifying and classifying production costs more accurately, following the methodological approach proposed by Peralta et al. (2024). Finally, the efficiency with which resources are used within the production system was evaluated in order to improve the planning for the execution of the various activities.

Afterwards, all data was organised into categories of fixed, variable and operating costs to determine the function and cost structure associated with the productive stages of breeding and milk production. In addition to this, the materials and inputs commonly used in the livestock system have been calculated on a unit basis, allowing for a comprehensive assessment of performance.

***GIS and Biodiversity Analysis*:** Following the Gabriele et al. (2023) and Mohammed Hamud et al. (2019) methodology, spatial information segments were processed based on land use, vegetation cover, and water resources. Spatial patterns of land use were analysed to assess ecosystems, using remote sensing and georeferenced property boundaries, with QGIS version 3.22. Plant biodiversity, on the other hand, was assessed through species richness, counting the total number of species in each sampling unit. Based on this data, we proceeded to calculate the Shannon diversity index (H′) using standardised ecological formulas. Soil quality was estimated using a composite index that integrated variables such as organic matter content, structure and soil cover, expressing it on a normalized scale from 0 (or low quality) to 1 (or high quality).

***Data Analysis*:** Quantitative data were analysed using descriptive statistics and cost benefit analysis to evaluate economic performance as well as an ANOVA in SAS version v. 9.4. (SAS Institute Inc., Cary, NC). while GIS-based spatial analysis supported the visualization of land use distribution

and biodiversity hotspots. The integration of economic and ecological datasets allowed for the identification of sustainable management strategies applicable to agroecosystems in Chimborazo.

RESULTS AND DISCUSSION

***Productive analysis*:** Within the fieldwork carried out for this research, the first point to be addressed was the productive analysis of the farm, given that milk production is directly related to each of its financial components. Milk production is directly related to each of the farm's financial components. To this end, an exhaustive review of the production logs for the year in question was carried out, compiling and tabulating the most relevant information for this item, mainly: volume of milk obtained in daily milkings, number of animals in production, date of registration, number of dry animals, number of pregnant animals, and number of milkings performed.

Table 1. Descriptive statistics by month.

Month	N	Minimum	Maximum	Mean	Standard deviation
January	20	540.00	594.00	578.20	16.93
February	20	578.00	700.00	650.20	24.21
March	21	640.00	724.00	690.00	21.05
April	20	690.00	750.00	728.30	21.03
May	20	708.00	738.00	716.60	8.11
June	20	692.00	718.00	702.20	7.73
July	20	680.00	694.00	684.70	4.17
August	20	622.00	672.00	648.60	13.52
September	20	600.00	612.00	606.00	3.37
October	20	594.00	608.00	601.50	3.03
November	20	580.00	596.00	589.70	3.69
December	20	572.00	592.00	583.60	5.97

Given that, as mentioned previously, many economic transactions are carried out on a monthly basis within the fiscal year, such as payments to suppliers of various inputs or payments for services rendered, it was appropriate to statistically analyze the data relating to monthly milk production (Vargas et al., 2021; Xu et al., 2018), mainly through the application of statistical tests that would reveal whether there were statistical differences between the milk production data for each of the months evaluated. To this end, the ANOVA test was applied, obtaining the results described in Table 2, where it can be verified that there were significant differences between the data groups for the volume of milk obtained in each of the months ($P < 0.01$), from which it can be concluded that production was not homogeneous throughout the year, which is due to the normal productive behavior of cows during lactation (Bytyqi et al., 2010), that is, within the total time during which the animals are productive between calving and calving, the amount of milk they produce varies, with peaks in production in specific months and lower yields in the remaining months while they are lactating (Orjales et al., 2019).

Table 2. Anova Test of Monthly Milk Production Results.

Source of variation	df	Mean Square	F	P value
Between Groups	11	61,178.447	340.42	0.001
Within Groups	229	179.717		
Total	240			

Given that there were statistical differences between the monthly milk production data sets, Tukey's test was applied to generate homogeneous groups, as shown in Table 3, with May and April recording the highest milk yields (with an average of 716.60 and 728.30 liters, respectively), while the group of months with the lowest production was represented by January, December, and November, with an average production of 578.20, 583.60, and 589.70 liters, respectively. while the remaining groups showed intermediate production between the months mentioned, with a decrease in the volume of milk obtained in the months closest to December and an increase in the months closest to April. Based on the normal production cycle of cows, it can therefore be said that peak lactation days occur in April.

Table 3. Monthly milk production.

Month	Mean Milk Production (L)	Homogeneous Group
January	578.2	A
December	583.6	A
November	589.7	A,B
October	601.5	B
September	606.0	B
August	648.6	C
February	651.0	C
July	684.7	D
March	691.1	D,E
June	702.2	E
May	716.6	F
April	728.3	F

^{A,B,C,D} Means with different letters in the same row differ at $P < 0.05$

In contrast, if the opposite of the case described in the previous section is implemented, taking the months with lower production as a reference would limit the availability of resources for much-needed actions, such as genetic improvement, facility maintenance, research into improved management, hiring of specialized personnel, participation in promotional events, farm growth, among other forms of investment that are often management actions that are not considered when cash flows decline, and that allow for the farm's longevity, increased production, increased production efficiency, and opportunities for business diversification

Table 4. Integration of GIS and Biodiversity Management Indicators in Agroecosystems of Chimborazo.

Farm /plot	Land use type	Area (ha)	Species Richness	Shannon Index (H')	Soil Quality Index	Notes on Management Practices
Plot 1	Pasture	12.5	8	1.92	0.78	Rotational grazing; mixed forage species
Plot 2	Silvopastoral	9.0	15	2.45	0.85	Native trees + pasture; shade for livestock
Plot 3	Crop + Livestock	7.2	10	2.01	0.80	Intercropping with maize; seasonal grazing
Plot 4	Riparian buffer	3.5	20	2.88	0.92	Vegetative buffer along river; high biodiversity
Plot 5	Pasture	15.0	7	1.75	0.74	Continuous grazing; monoculture grass

(Walther et al., 2022). That is why the changing dynamics of animal production cycles must be considered in the stages of production and financial planning (Ortigues-Marty et al., 2019). It is necessary for management personnel, within the financial planning phases, to consider the variability in animal production so that cash outflows are in line with cash inflows from milk production, thereby maintaining economic balance throughout each of the periods into which financial activities are divided (Mazzetto et al., 2015).

It is important to establish homogeneous groups in milk production and to determine the months of highest and lowest productivity, given that, in order to maintain an economic balance that favors the farm, the flow of income must be proportional to the amounts to be paid out for monthly obligations to staff, suppliers, and other creditors (Orjales et al., 2019). However, if a constant cash flow is not maintained over time due to the non-homogeneous production of the animals, the planning of resource-consuming activities must be equivalent to the expected monthly production, given that if the months of highest production are taken as a reference for income flows, in the remaining months, where the volume of milk is lower, there will not be sufficient working capital to meet liabilities, resulting in negative cash flows that put the farm at risk.

Among the results, we obtained consistent relationships between soil type, biodiversity, and management practices implemented in the evaluated agroecosystems. Plot 2 (managed under silvopastoral systems) and plot 4 (riparian buffer zones) showed the highest species richness indices with 15 and 20 species respectively, along with the highest Shannon values (2.45 and 2.88). Based on these findings, including the analysis of the tree component and native vegetation, there is a push towards greater biological diversity in livestock systems in the high Andean region of Ecuador (Guamán-Rivera et al., 2024; Martínez et al., 2014). In contrast, there has been evidence of a greater presence of grasses managed as monoculture in plots 1 and 5, which explains the low plant diversity observed (7 and 8 species, on average) and Shannon index (1.75-1.92), classified as having a simplified ecological structure (Fuentes et al., 2023). Along the same lines, plot diversification leads to better soil quality, highlighting the interactions that occur when there are synergies between biodiversity and functionality (Makhathini et al., 2023).

Table 4 summarises that GIS applicability is a powerful methodological tool when attempting to quantify spatial patterns of land use, as well as vegetation cover across a wide range of livestock systems (Arévalo-Ramírez et al., 2022; Villacrés and Auat-Cheein, 2022). Combining ecological and management indicators, together with spatial data, makes it possible to identify how the application of clean technologies contributes, in addition to ecosystem services, to improving production rates (Hazwan et al., 2022). Based on this, it is reaffirmed that innovative practices such as agroforestry systems represent a sustainable production alternative for the high Andean livestock system in the central highlands of Ecuador (Horan et al., 2018).

***Determination of income from the sale of milk*:** In terms of productivity, the total milk produced during the year under study was 156,282.2 litres, while the average milk/cow/day was 8.92 litres. It should be noted that, according to Ecuadorian national regulations, the official price for the sale of raw milk is 0.52 cents. However, due to the quality of the milk, companies in the area penalise this farm and pay 0.42 US cents. For this reason, the income from milk sales is 78,141.41 US dollars.

Table 5. Operating costs for the sale of raw milk.

Criterion	Value	Unit
Total milk production, year	156,282.20	L/year
Daily production, mean	428.17	L/day
Milk/cow/d	8.92	L/animal
Cost as 1L	0.43	$/L
Income for sale of milk	67,201.34	$

***Conclusions*:** Under high Andean conditions in Ecuador, this initial study demonstrated that the combination of economic indicators and the use of GIS tools has made it possible to assess the level of sustainability of livestock production. Similarly, seasonality conditions production levels, directly affecting the financial statements of livestock farming, while, at the same time, the implementation of silvopastoral systems improves soil quality and, consequently, the biodiversity of the system.

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***Consent to participate*:** All participants consented for this research study

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***SDGs addressed*:** Good health and well-being

***Policy referred*:** Ecuador's National Climate Change Strategy (ENCC), National Policy for Sustainable Livestock Development

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